Coal and Renewables in an Externality-Constrained Energy Economy: Competitive and Cooperative Strategies

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Viewgraphs for Presentation
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- H_2/electricity economy studies (*Carbon Mitigation Initiative*)
  - H_2/electricity production
    - Tom Kreutz, Luca de Lorenzo, Robert Socolow, Bob Williams (*PEI*)
    - Paolo Chiesa, Stefano Consonni, Giovanni Lozza (*Politecnico di Milano*)
  - H_2/CO_2 infrastructure/H_2 end-use technologies
    - Joan Ogden (*now at UC Davis*), Bob Williams (*PEI*)
- China "coal polygeneration" studies
  - Eric Larson, Fuat Celik, Bob Williams (*PEI*)
  - Li Zheng, Ni Weidou, Ren Tingjin (*Tsinghua University*)
- Wind/CAES energy studies
  - Jeff Greenblatt, Samir Succar, David Denkenberger, Bob Williams (*PEI*)
- Biomass energy studies
  - Eric Larson, Fuat Celik, Bob Williams (*PEI*)

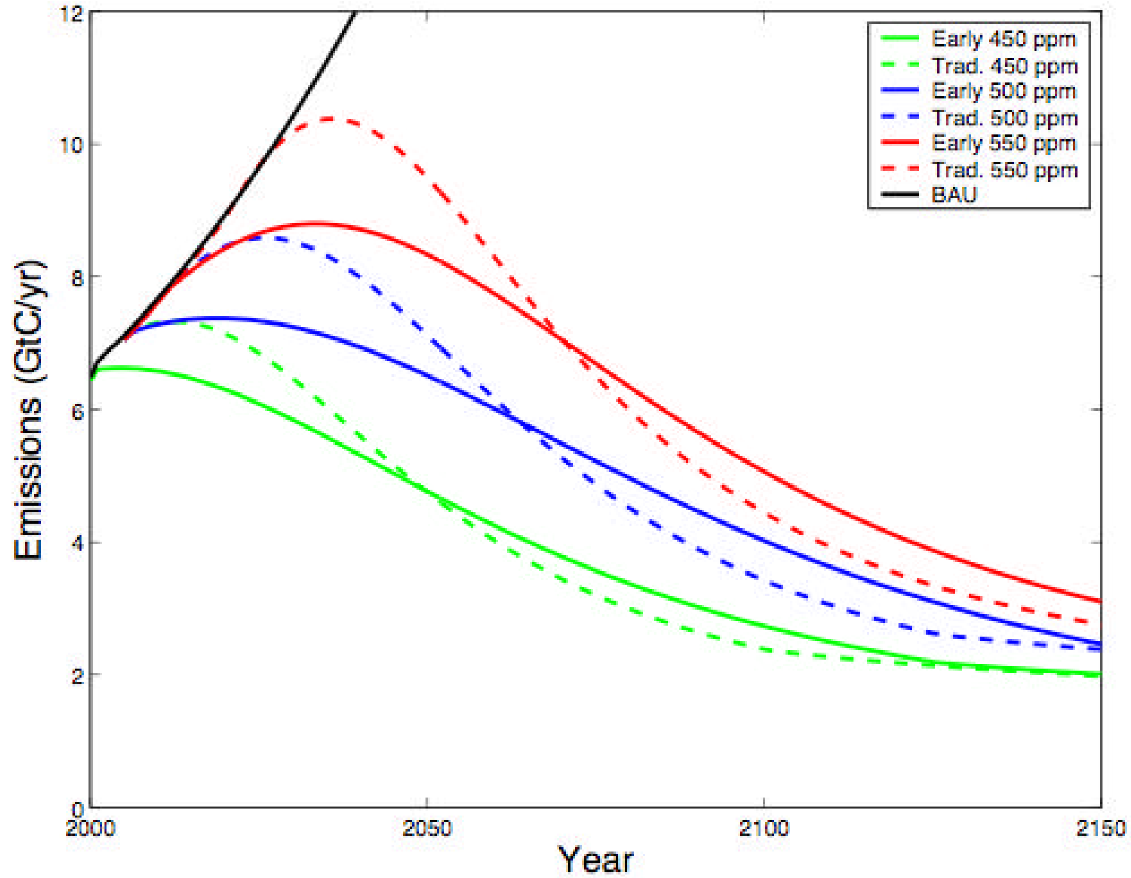
MAJOR CHALLENGES POSED BY FOSSIL FUELS

- Air pollution

  (*esp. human health damages from* $PM_{2.5}$; *Hg = emerging issue*)
- Oil issues

  (*supply insecurity*, *oil price)*
- Climate change

  (*most daunting challenge)*



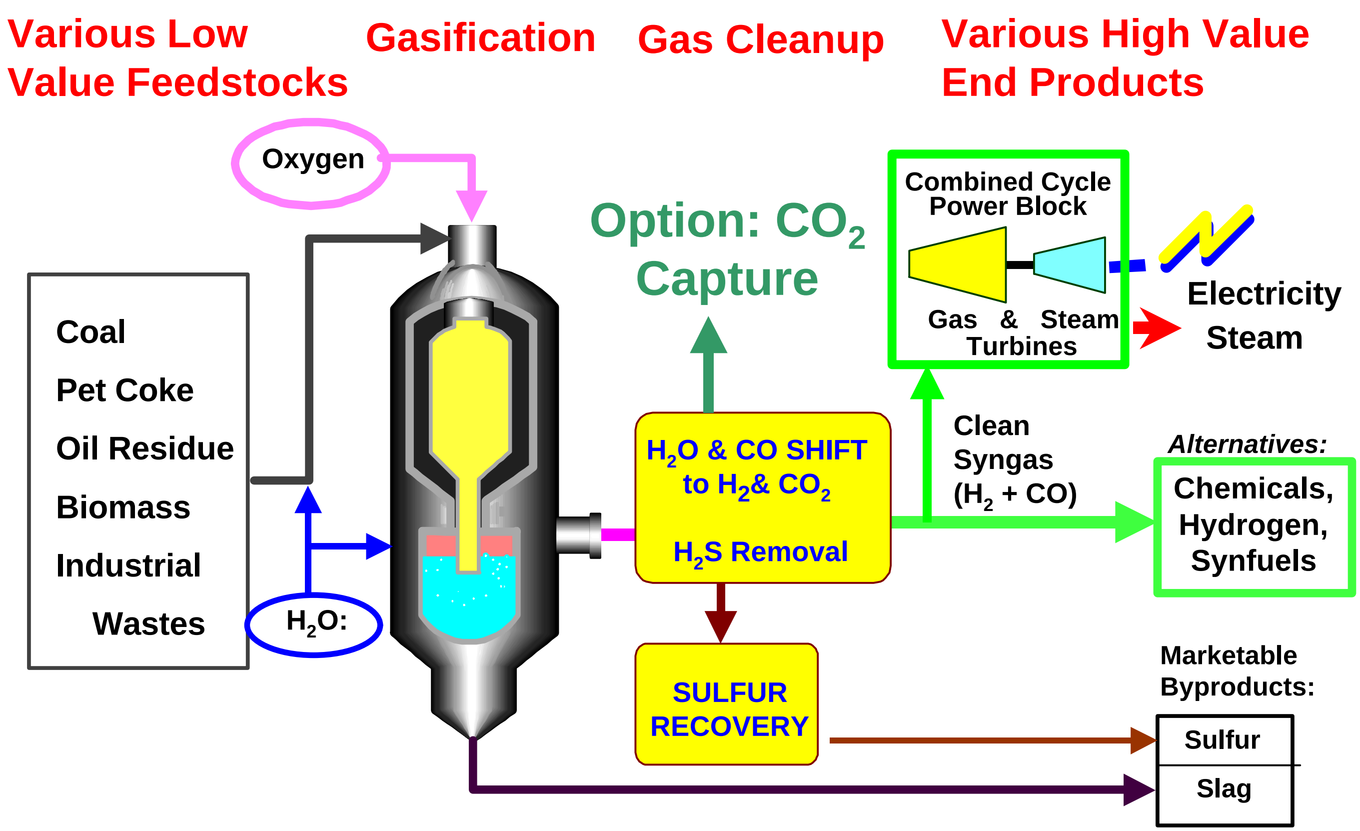
CLIMATE CHANGE MITIGATION CHALLENGE:

- **World with 10 billion people & ¼ US emission rate ➔ 14 GtC/y**
- **Stabilizing atmospheric CO_2 at $\leq$ 2X pre-industrial level**
  - **➔ CO_2 emission rate in 2100 ~ 3 to 5 GtC/y**
  - **➔ De-emphasize FFs, pursue gigascale CO_2 capture/storage, …or both**

COAL: CHALLENGE…AND OPPORTUNITY

- Coal = <u>main</u> challenge for energy w/r to climate change
- Also severe air pollution problems, mining hazards
- Coal not likely to be abandoned because of:
  - Coal abundance
  - Low, non-volatile coal prices
- Can technology make coal environmentally acceptable?
  - Gasification + CCS promising in addressing *all three major challenges posed by fossil fuels…but only if geological CO_2 storage proves to be widely viable*
  - Residual environmental, health, safety problems of coal mining

GASIFICATION TO CONVERT LOW-VALUE FEEDSTOCKS INTO HIGH-VALUE PRODUCTS



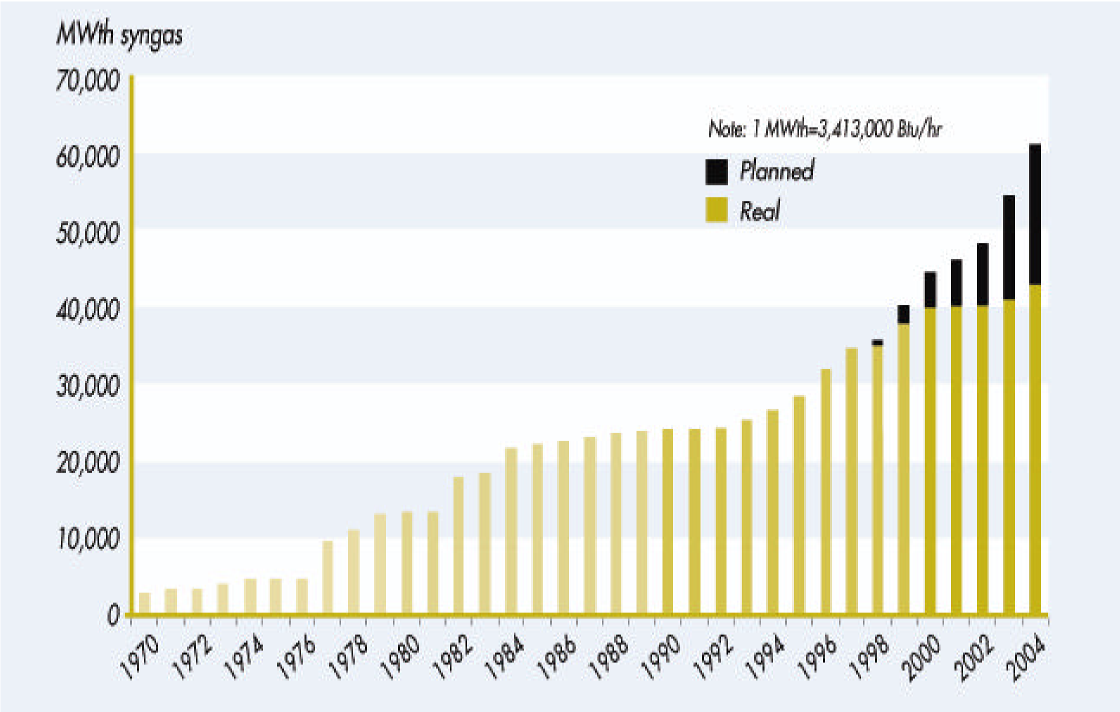
WGS ($CO + H_2O \rightarrow H_2 + CO_2$) is key both to creation of high-value products and to decarbonization for climate-change mitigation

EIA 2003 PROJECTION OF WORLD COAL USE

	Energy Use (Quads/y)			CO_2 emissions (Gt C/y)		
	2000	2025	2000-2025 increment	2000	2025	2000-2025 increment
Coal use						
China	24	54	30	0.59	1.35	0.76
Other LDCs	19	28	10	0.48	0.73	0.25
Total LDCs	**43**	**82**	**40**	**1.07**	**2.08**	**1.01**
US	20	27	7	0.58	0.75	0.17
Other ICs	31	29	-2	0.71	0.68	- 0.04
Total ICs	**51**	**56**	**5**	**1.29**	**1.43**	**0.13**
Total world coal use	**94**	**139**	**45**	**2.37**	**3.51**	**1.14**
Total world energy use	**399**	**640**	**241**	**6.42**	**10.36**	**3.94**

If gasification is to "save coal," wide LDC use will be crucial.

GASIFICATION IS BOOMING GLOBAL ACTIVITY



Worldwide gasification capacity is increasing by 3 GW_{th} per year and will reach 61 GW_{th} in 2004

- **In 2004**
- By activity:
- 24 GW_{th} chemicals
- 23 GW_{th} power
- 14 GW_{th} synfuels
- By region:
- 9 GW_{th} China
- 10 GW_{th} N America
- 19 GW_{th} W Europe
- 23 GW_{th} Rest of world

By feedstock:

- 27 GW_{th} petroleum residuals
- 27 GW_{th} coal
- 6 GW_{th} natural gas
- 1 GW_{th} biomass

Most gasification is for polygeneration in making chemicals/oil refining

MAJOR GASIFICATION-BASED ENERGY OPTIONS

- IGCC with CCS—*by wide margin, least costly option for decarbonizing new bituminous coal power plants*
- H_2 from coal with CCS—*least costly H_2 option with near-zero CO_2 emissions*
- Liquid fuels via indirect coal liquefaction with CCS
  - Fuel-cycle wide GHG emissions can be less than for crude-oil derived fuels
  - Choice of super-clean designer fuels can facilitate shift to super-efficient vehicles (e.*g.*, *to hybrid-electric compression-ignition engine cars*)
- Polygeneration strategy for integrating all 3 options

COAL AND RENEWABLES

- If geological CO_2 storage proves to be viable at gigascale, what are implications for renewables? Consider separately electricity and fuels used directly
- In electricity markets, renewables will be strong competitors to decarbonized coal with CCS. Illustrate with comparative cost analyses for:
  - Coal IGCC with CCS
  - Wind/CAES systems for baseload power
- For markets that use fuels directly, consider separately:
  - Providing H_2 with near zero emissions of GHGs:
    - Coal H_2 with CCS very promising…if geological storage viable at gigaascale
    - But H_2 economy is decades away
  - Providing carbon-based fuels
    - Biofuels promising locally…but globally land-use constrained
    - Especially promising medium-term option:coal/biomass co-processing with CCS to produce “designer fuels” used with energy-efficient end-use technologies

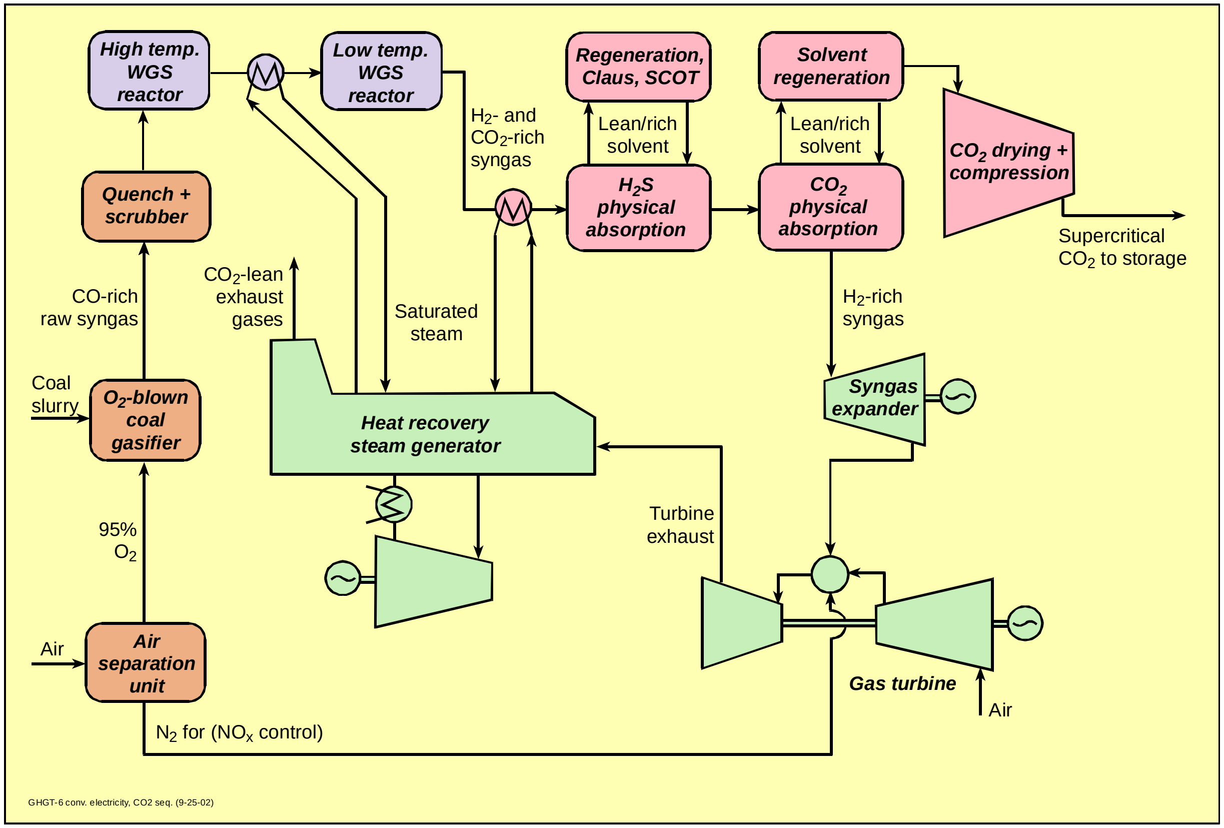
Distribution of Global CO_2 Emissions from FFs (%)

Year	2000	2020	2050
Electricity generation	36	25-38	22-43
Industry	32	28-32	24-37
Transportation	21	21-25	18-33
Residential/commercial	12	12-20	11-19

Must decarbonize fuels used directly (FUD) well as electricity

IEA data for 2000. Projections are for A1B-AIM, AIT-Message, A2-Image, B1-Image, B2-Message scenarios of IPCC's *Special Report on Emissions Scenarios* (IPCC, 2000)

Coal IGCC with CCS



- **w/o CCS, IGCC ➔ electricity from coal with AP emissions as low as for NGCC**

- **Pre-combustion capture of CO_2 at high partial P ➔ IGCC = least-costly option for decarbonizing bituminous coal electricity** (*~ 35-50% cost penalty*)

…But IGCC with CO_2 vented not less costly that coal steam-electric power

…and ~ \$80-\$100/tC carbon tax needed to induce CCS

GENERATION COST FOR COAL IGCC WITH CCS

430 MW IGCC w/CCS (*E-Gas*), CF = 90%	¢/kWh
Capital (*TPI ~ \$2000/kW, LACCR = 0.154*)	3.90
Fuel (*ç = 30.5%, \$1.16/GJ*)	1.37
O&M	0.95
CO_2 transport & storage (*@ \$4.8/t CO_2*)	0.43
Total	6.63
CO_2 emission rate (*gCO_2/kWh*)	135
CO_2 storage rate (*gCO_2/kWh*)	889

<u>Source</u>: EPRI, *Phased Construction of IGCC Plants for CO_2 Capture: Low-Cost IGCC Plant Designs for CO_2 Capture*, 2003

COMPETITION FROM WIND/CAES IN BASELOAD POWER MARKETS

- Wind power costs have fallen to ~ 5 US cents/kWh range
- US electricity use: **3,600 TWh** (2001); only 0.5% wind-generated
- U.S. wind potential: **~10,600 TWh/y** ➔ …under carbon constraint, can wind compete with coal?
- Resource concentrated in sparsely populated Great Plains
- Such remote wind resources could be exploited if converted via appropriate storage into baseload power and transmitted to market via HV transmission
- Compressed air energy storage (CAES) is strong candidate technology for this role—wind/CAES connection pioneered by Al Cavallo (1995)

ATTRACTIVE CAES DAY-LONG STORAGE COSTS ➔ CAES/WIND HYBRID FOR BASELOAD POWER

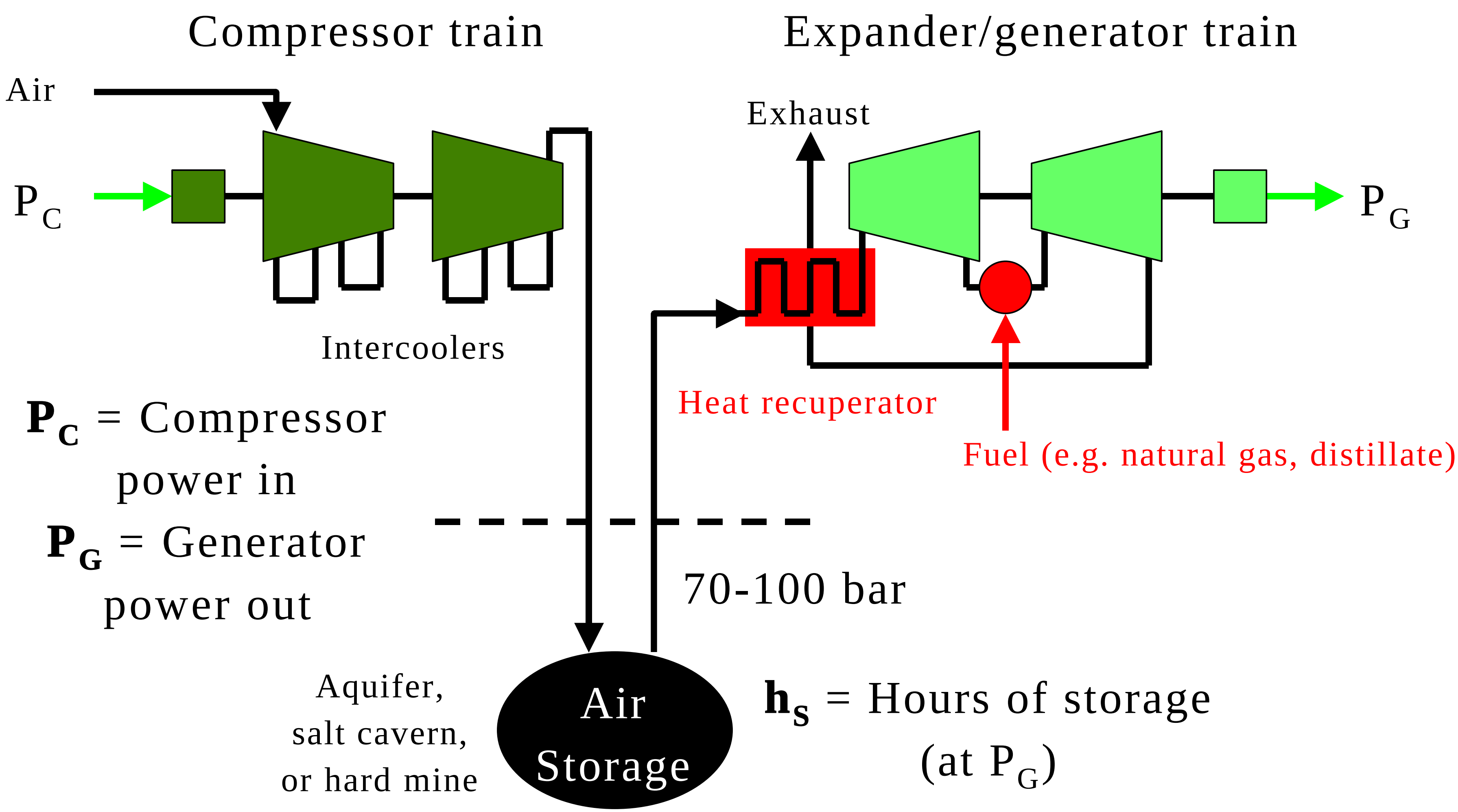
Electric storage options

Technology	Capacity ($/kW)	Storage ($/kWh)	Cost with 20 hrs. storage ($/kW)
Compressed Air Energy Storage (CAES) (300 MW)	**440**	**~1**	**460**
Pumped hydroelectric	900	10	**1100**
Advanced battery (10 MW)	120	100	**2100**
Flywheel (100 MW)	150	300	**6200**
Superconductor (100 MW)	120	300	**6100**

CAES is clear choice for:

- Several hours (or more) of storage
- Large capacity (300 MW)

CAES system

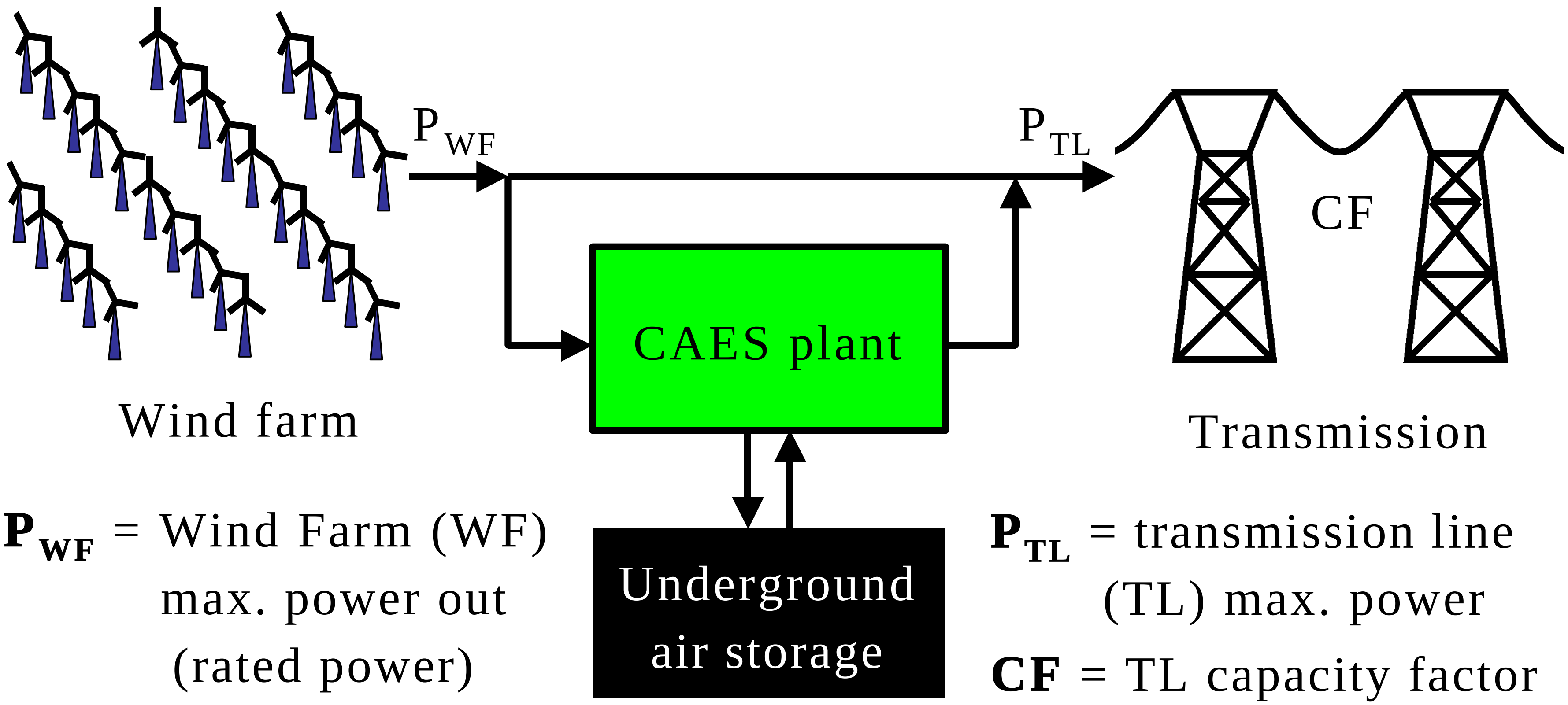


$\mathbf{P_C}$ = Compressor power in

$\mathbf{P_G}$ = Generator power out

$\mathbf{h_S}$ = Hours of storage (at P_G)

A wind/CAES model



$\mathbf{P_{WF}}$ = Wind Farm (WF) max. power out (rated power)

$\mathbf{P_{TL}}$ = transmission line (TL) max. power

CF = TL capacity factor

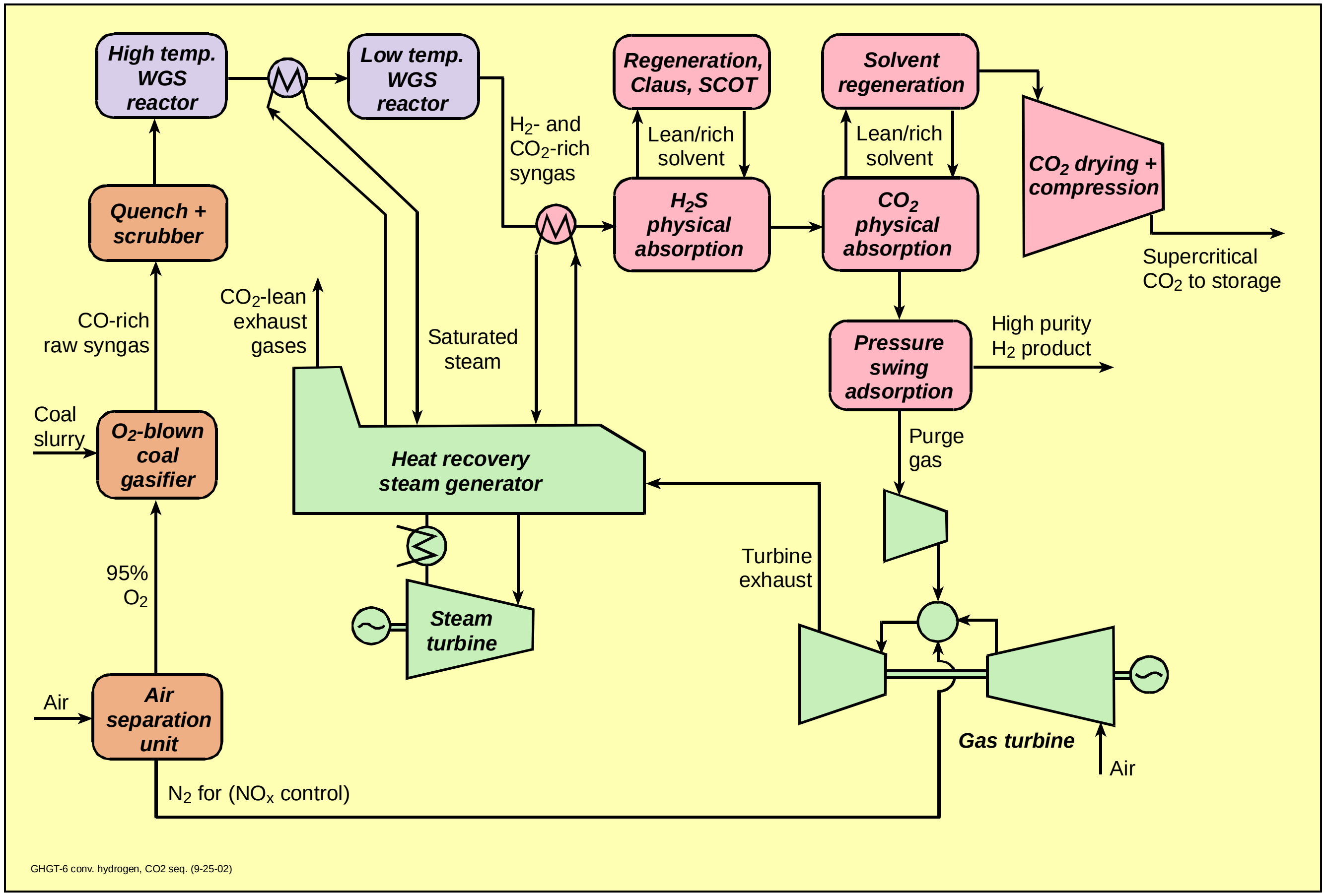
With current technology baseload wind/CAES power at typical US Great Plains sites can be put onto TL for ~ 6 US ¢/kWh… ~ cost of coal IGCC with CO_2 capture and storage

COST FOR 2 GW_e WIND/CAES SYSTEM, CF = 90%

Wind Farm [*Class 5 wind (7.8 m/s); 58% of output to TL, 42% to CAES*]	¢/kWh
Capital (*4.3 GW @ \$923/kW$_e$*)	3.83
O&M (*0.5 ¢/kWh of WF output*)	0.43
Land royalties (*2.5% WF busbar cost: 72 • 10^3 ha @ \$238/ha/y*)	0.11
CAES (*2.0 GW expander, 2.3 GW compressor, 53 h storage*)	
Capital (*\$170/kW exp; \$155/kW comp; \$170/kW BOS; \$1/kWh stor*)	1.08
O&M (*fixed @ \$13/kW-y, variable @ 0.15 ¢/kWh*)	0.22
Fuel [*\$4.64/MBTU (NG), 4200 BTU/kWh expander out*]	0.81
Total	6.48
CO_2 emission rate for system (*g CO_2 per kWh for system*)	101

CAES adds 1.4 ¢/kWh to WP cost @ CF = 90%, 1.1 ¢/kWh @ CF = 80%

H_2 FROM COAL with CCS



Coal H_2 w/CCS: least-costly H_2 option (*~ \$1.0 to \$1.2/kg with current technology*) **with near-zero GHG emissions** (*~ 20% cost penalty for CCS*)

…but H_2 end-use technologies (*e.g. fuel cell cars***) won't play large roles for decades…and developing H_2 economy infrastructure will take decades**

NON-FOSSIL FUEL C-FREE OPTIONS FOR FUD

- Biofuels…but there is not enough land for biofuels alone to do the job:
  - ~ 475 EJ/y of FUD needed for world with 10 billion people if average per capita FUD rate = 0.25 x US rate
  - World Energy Assessment (2000) estimates long term biomass production rate for energy ~ 100-300 EJ/y ➔ 60-180 EJ/y of fluid biofuels

- Electrolytic H_2 (*wind*, *PV*, *or nuclear*) or thermochemical H_2 (*solar thermal or nuclear*)…but these options with hoped-for future advanced technologies are much more costly than for coal H_2 with CCS based on commercially-ready technology (US National Research Council, 2004) …and shift to such technologies would be economically burdensome, especially to developing countries

Growing Middle East tensions plus constraints on world oil production

DATE OF WORLD OIL PRODUCTION PEAK

Alternative estimates of EUR conventional oil (*10^9 barrels*)	1800	2400	3000
Peak with no unconventional oil	2001	2012	2021
Peak if GTL is only unconventional oil (*360 x10^9 barrels from 2000 TCF NG*)	2008	2017	2025
Peak if Canadian tar sands also included (*300 out of 1700 x 10^9 barrels OOIP*)	2013	2021	2028
Peak if Venezuelan heavy oil also included (*272 out of 1200 x 10^9 barrels OOIP*)	2017	2025	2032

Without expansion of Middle East capacity, peak would occur earlier

CLEAN SYNFUELS FROM COAL IN CLIMATE-CONSTRAINED WORLD?

- Rationale for exploring possibilities:
  - Oil supply concerns (*strong coal synfuels interest in China*)
  - H_2 FCVs cannot make major transportation contributions until 2nd Qtr 21st century
- Approach:
  - Focus on clean "designer" fuels to facilitate shift to more efficient (CI) engine vehicles (*by reducing requirements for tailpipe emission controls*)
  - Explore early opportunities for CCS (*even before climate policy enacted*) via CO_2/H_2S co-capture/co-storage as acid gas management strategy
  - Explore opportunities for coprocessing coal and biomass

LIQUID FUELS FROM COAL

<u>Challenge</u>: increase H/C ratio (*H/C ~ 2 for HC fuels; ~ 0.8 for coal*)

- Gasify coal in O_2/H_2O to produce "syngas" (*mostly CO, H_2*)
- Increase H/C ratio via WGS to maximize conversion in synthesis reactor ($CO + H_2O \rightarrow H_2 + CO_2$)
- Remove acid gases (*H_2S and CO_2*), other impurities from syngas
- Convert syngas to synthetic fuel in "synthesis" reactor
- Can strive to make fuels superior to crude oil-derived HC fuels:

  (*i*) set goals for performance, air-pollutant emissions, cost;

  (*ii*) seek chemical producible from CO, H_2 that comes closest to meeting goals;

  (*iii*) develop that chemical (*"designer fuel" strategy*)

SYNFUEL OPTIONS VIA COAL GASIFICATION

F-T Diesel → Blend with crude oil-derived Diesel

F-T Diesel → Use as substitute for crude oil-derived Diesel

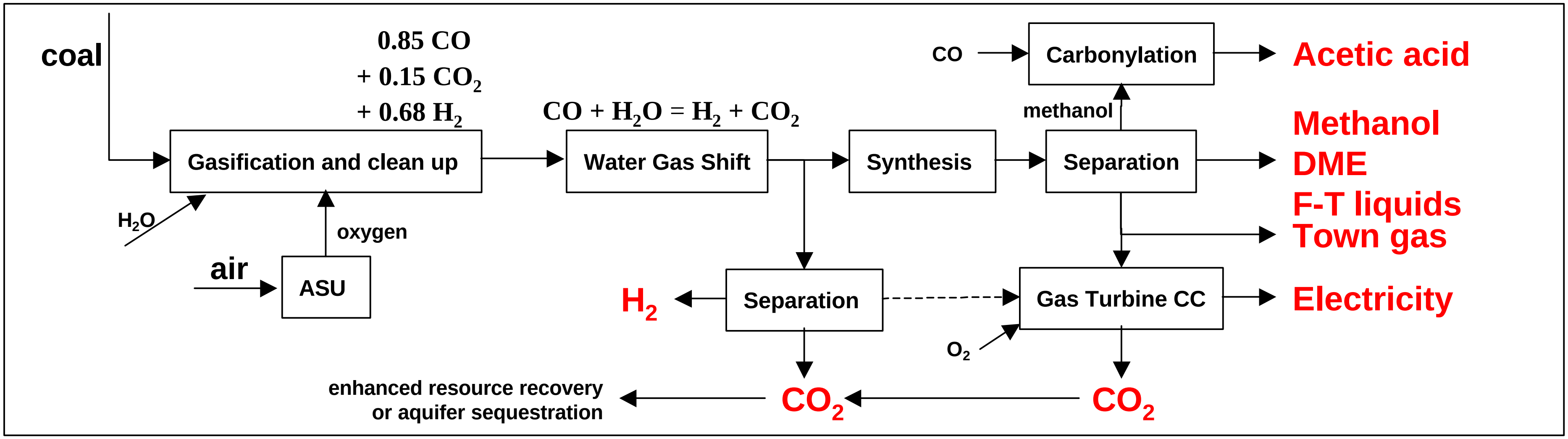
MeOH → Convert to gasoline (*Mobil process*)

MeOH → Use directly as fuel

MeOH → Convert to DME via dehydration

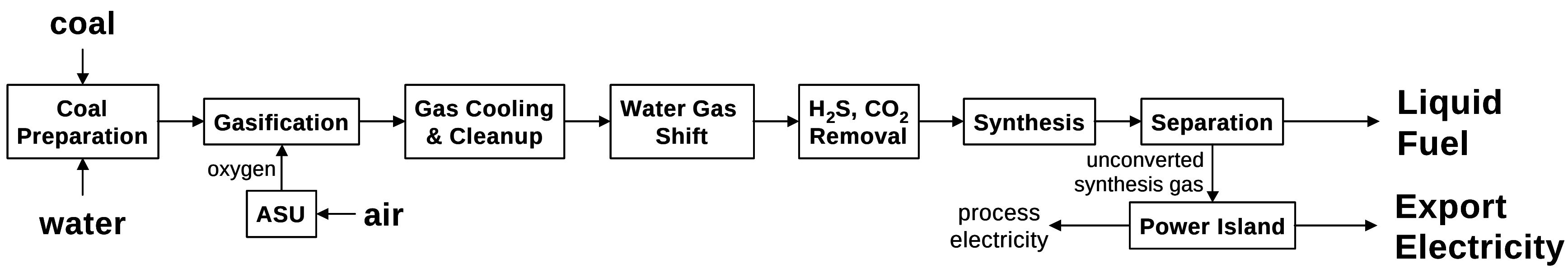
DME → Use directly as fuel

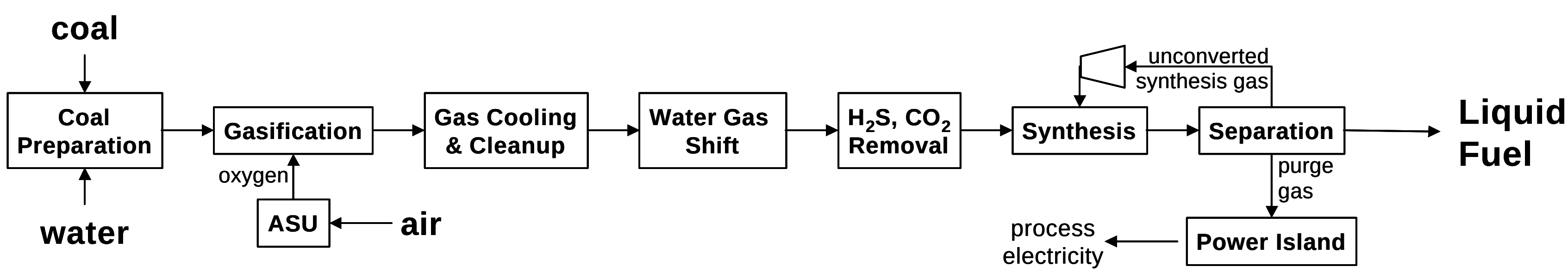
Coal polygeneration – general scheme



Co-production of synfuel and electricity (*or multiple products*) will often be favored. This "polygeneration" concept is "taking off" at refineries, chemical process plants worldwide and may soon be introduced for the production of synfuels (*China is the country to watch*). Producing high H/C ratio fuels from coal ➔ relatively pure CO_2 coproduct and low cost CO_2 capture costs for CO_2 captured prior to fuel synthesis.

ONCE-THROUGH (OT) vs RECYLE (RC) OPTIONS

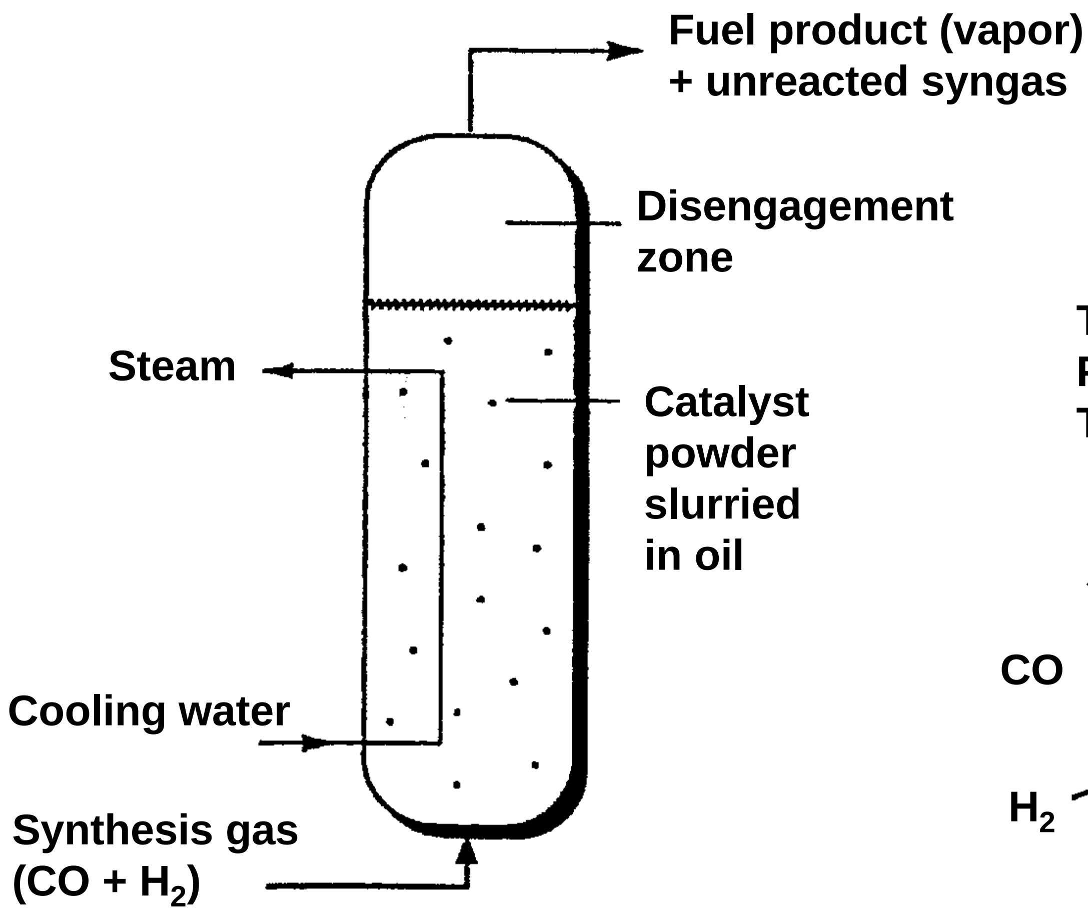




- <u>OT option</u> (*top*): syngas passes once through synthesis reactor; unconverted syngas burned electricity coproduct in combined cycle
- <u>RC option</u> (*bottom*): unconverted syngas recycled to maximize synfuel production; purge gases burned electricity for process; no electricity export
- OT systems especially attractive when using liquid-phase reactors that are well suited for use with CO-rich syngas

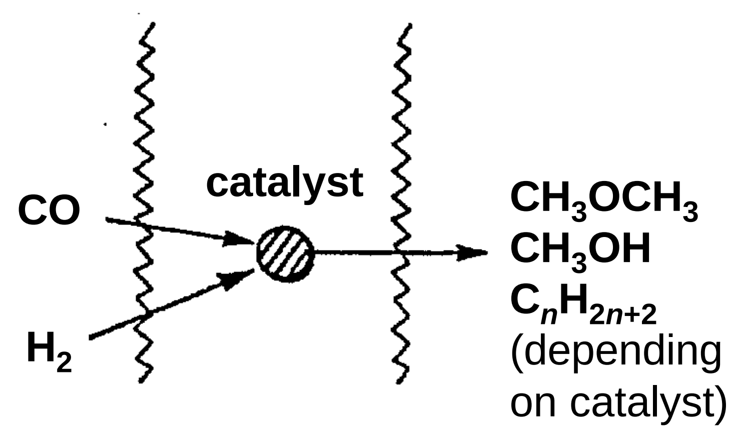
Liquid-Phase (LP) Synthesis Technology

Well-suited for use with
CO-rich (coal-derived) syngas



Liquid-phase reactors have much higher one-pass conversion of $CO+H_2$ to liquids than traditional gas-phase reactors, e.g., liquid-phase Fischer-Tropsch synthesis has ~80% one-pass conversion, compared to <40% for traditional technology.

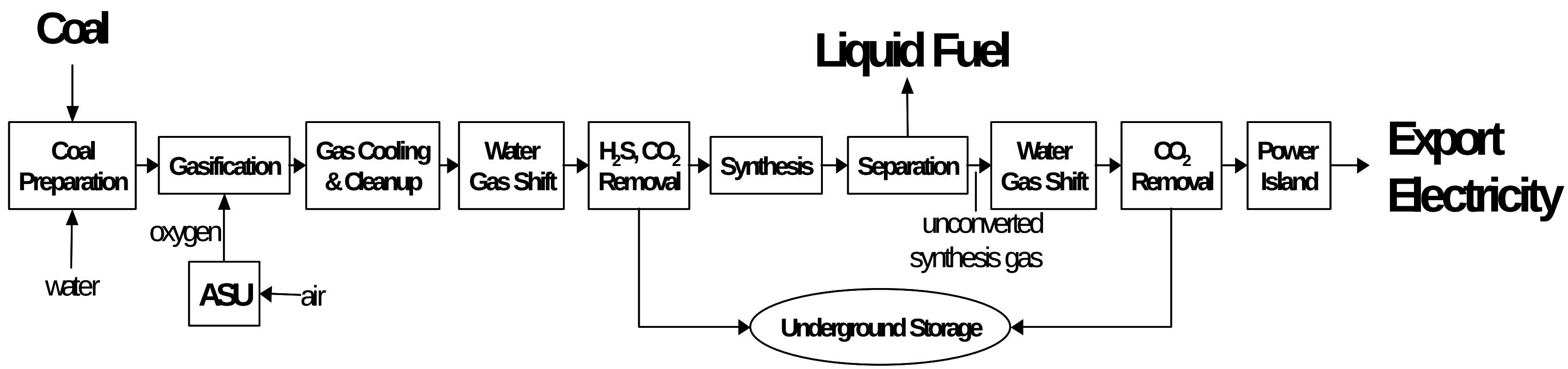
TYPICAL REACTION CONDITIONS:
P = 50-100 atmospheres
T = 200-300^{o}C



Status of LP Synthesis Technology

	Fischer-Tropsch	MeOH	DME
Commercial units in operation	✓		
Demonstrated at commercial scale		✓	
Demonstrated at pilot-plant scale			✓

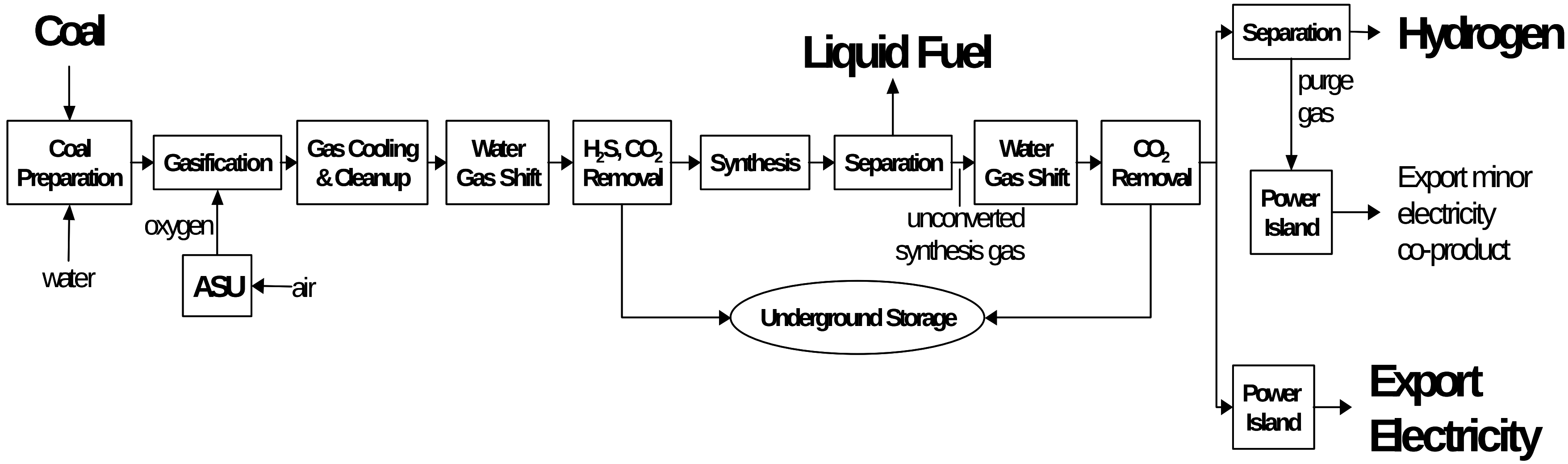
Under Climate Constraint, Coproduce Liquid Fuel + Electricity with CO_2 Capture Upstream and Downstream of Synthesis Reactor



Fuel cycle GHG emission rate for liquid fuels produced can sometimes be less than for petroleum-derived fuels

Upstream (partial) decarbonization (co-capture/co-storage of CO_2 and H_2S) will sometimes be less costly as acid gas management strategy than capturing acid gases separately, venting CO_2 and reducing H_2S to S…even in absence of climate mitigation policy

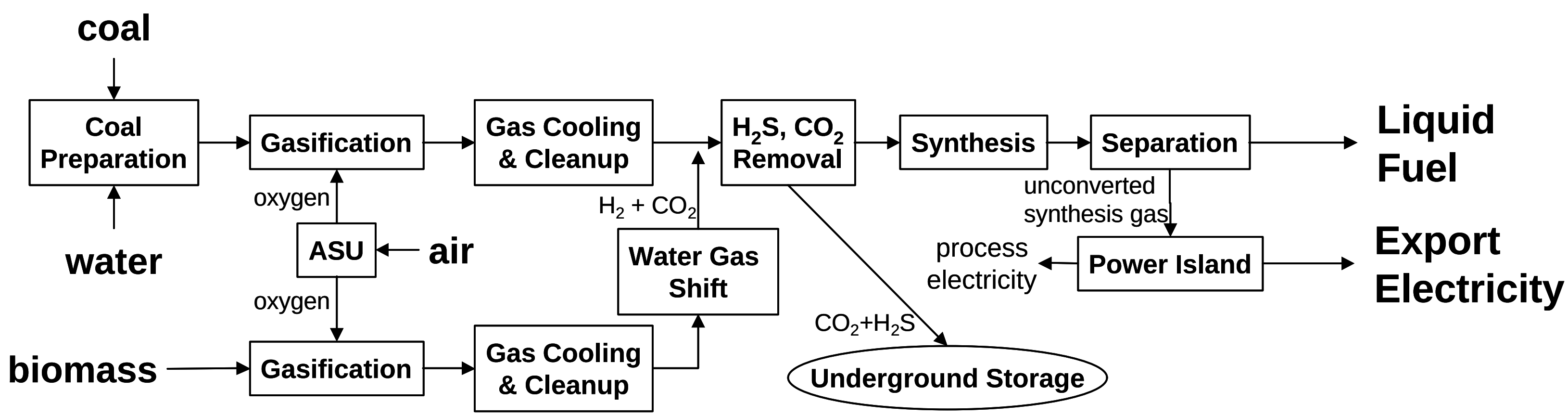
Decarbonized Coal Energy Coproduction in Long Term



By the time H_2 is launched in market as energy carrier:

- Decarbonized syngas downstream of liquid fuel synthesis reactor can be used to produce mix of electricity + H_2
- H_2/electricity output ratio would be determined mainly by relative H_2/electricity market demands because system efficiencies/costs invariant over wide range of H_2/electricity output ratios

COPROCESSING BIOMASS WITH COAL TO MAKE LIQUID FUELS PLUS ELECTRICITY



Alternative to shifting coal syngas to achieve desired H_2/CO ratio for synthesis: provide H_2 from biomass via gasification & store CO_2 coproduct underground ➔ "negative" CO_2 emissions for biomass will partially offset CO_2 emissions from synfuel combustion

➔synfuels with low net CO_2 emissions using much less land than for "pure" biofuels

CANDIDATE DESIGNER FUEL: DME (CH_3OCH_3)

- Ozone-safe aerosol propellant and chemical feedstock
- Production ~ 150,000 t/y by MeOH dehydration (*small plants*)
- Prospective clean cooking fuel—LPG supplement—esp. for LDCs
- Prospectively good compression-ignition engine (*CIE*) fuel:
  - high cetane #
  - no sulfur, no C-C bonds that could lead to soot ➔ no PM/NO_x tradeoff in quest for low emissions, so low NO_x emission rate readily achievable
- Drawbacks:
  - Gas at atmospheric pressure—mild pressurization (*as for LPG*) needed
    ➔ need new infrastructure for transport applications
  - Further engine developments needed before DME is ready for transport markets
- Production plans:
  - NG DME: 110,000 t/y (Sichuan, China, 2005); 800,000 t/y (Iran, 2006)
  - Coal DME (800,000 t/y project approved, Ningxia, China)

Single-Step DME synthesis

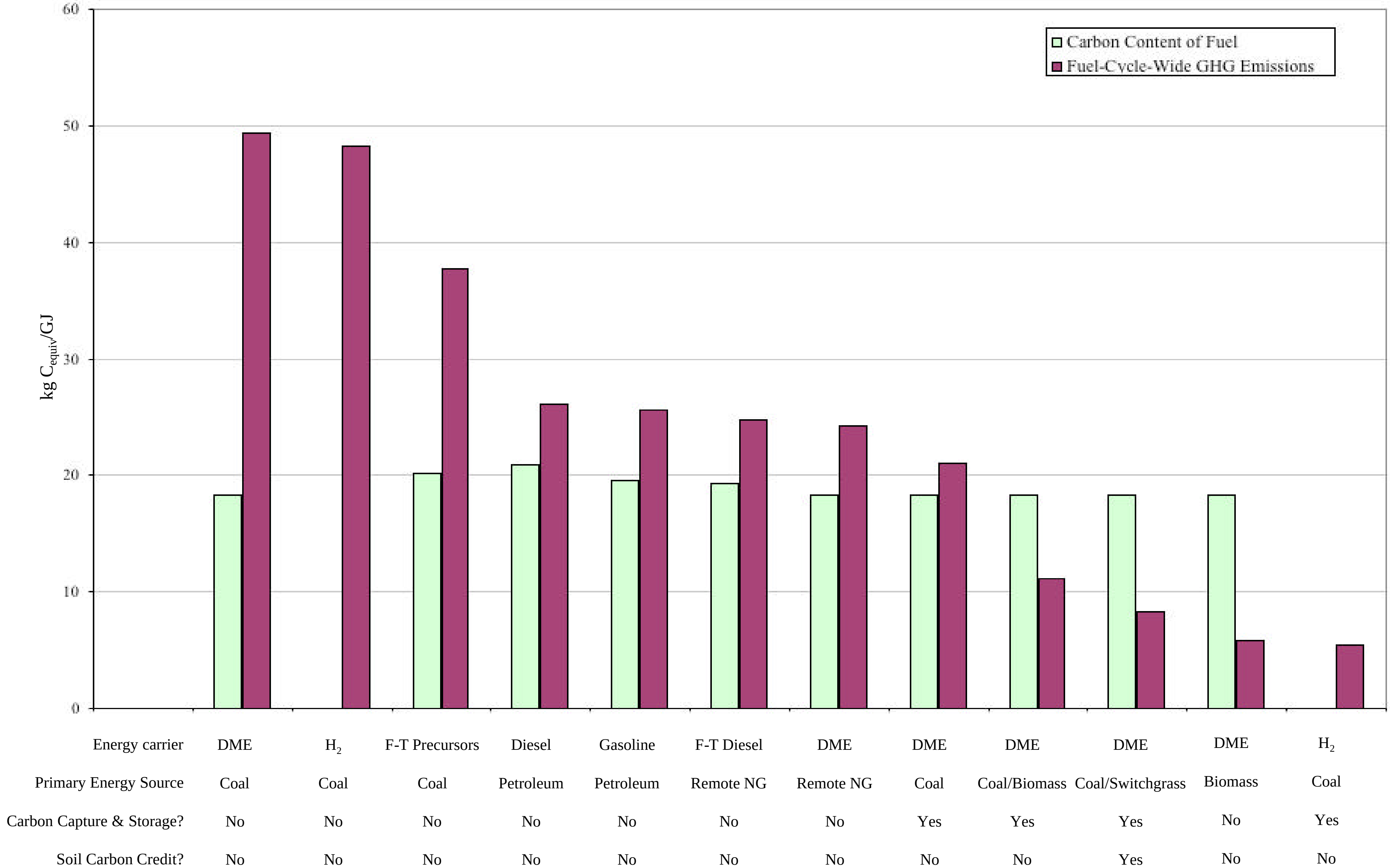
$$CO + 2H_2 \Leftrightarrow CH_3OH \qquad \text{(MeOH synthesis)} \qquad -91 \text{ kJ/mol}$$

$$2CH_3OH \Leftrightarrow CH_3OCH_3 + H_2O \qquad \text{(dehydration)} \qquad -24 \text{ kJ/mol}$$

$$H_2O + CO \Leftrightarrow H_2 + CO_2 \qquad \text{(water gas shift)} \qquad -41 \text{ kJ/mol}$$

- One original motivation for DME: higher conversion feasible than with MeOH (*MeOH formation is equilibrium limited but dehydration removes MeOH as it forms, enabling equilibrium limit to be surpassed*).
- Two catalysts suspended in oil of synthesis reactor
  - $CuO/ZnO/Al_2O_3$ for MeOH synthesis, WGS
  - γ-alumina for MeOH dehydration

Fuel Carbon Content & Fuel-Cycle-Wide GHG Emissions For Alternative Energy Carriers/Primary Energy Sources



US SWITCHGRASS PRODUCTION SCENARIO
(*current technology*)

Scenario developed in McLaughlin et al., 2002: High-value renewable energy from prairie grasses, *Envir. Sci.& Tech.*, **36** (10): 2122-2129:

- 2.9 EJ/y production (*9.4 t/ha/y*) on 19 $\cdot 10^6$ ha (~ *10% US cropland*)
- Soil C builds up @ 0.5 tC/ha/y, average for first 30 y
- Farmgate switchgrass price: \$44/t (*\$2.4/GJ*)
- Consider switchgrass for coal/biomass DME plant (*740 MW DME; 630 MW electricity*):
  - Switchgrass delivery rate: 3300 dry tonnes/day
  - Plantation area: ~ 1100 km^2

% of land in switchgrass	Distance (km)	Delivered cost
10	39	\$55/t (*\$3.0/GJ*)
20	27	\$53/t (*\$2.9/GJ*)
30	23	\$52/t (*\$2.8/GJ*)

US SCENARIO FOR DME FROM COAL/SWITCHGRASS

- Make 3.1 EJ/y of DME from:
  - 2.9 EJ/y switchgrass on 19 x 10^6 ha (*equivalent to ~ 10% of US cropland*)
  - 4.0 EJ/y coal (~ 20% *of US coal use rate*)
- DME could support $173 \cdot 10^6$ CIE/HE cars (*90% of US light-duty vehicles in 2000*) if fuel economy = 80 mpg_{ge}
- CO_2 storage rate ~ $300 \cdot 10^6$ t CO_2/y
- GHG emissions = 20 $\cdot 10^6$ t C/y (*vs 210* $\cdot 10^6$ *tC/y for 30 mpg gasoline cars*)
- Impact of $100/tC carbon valuation on net cost of switchgrass:

Cost without valuation of carbon	$2.9/GJ
Cost w/C valuation but neglecting soil C buildup	$1.4/GJ
Cost w/C valuation, including credit for soil C buildup	$1.1/GJ

➔ biomass, coal are “comparably ready” to help mitigate climate change

OUTLOOK FOR AUTO FUEL ECONOMY

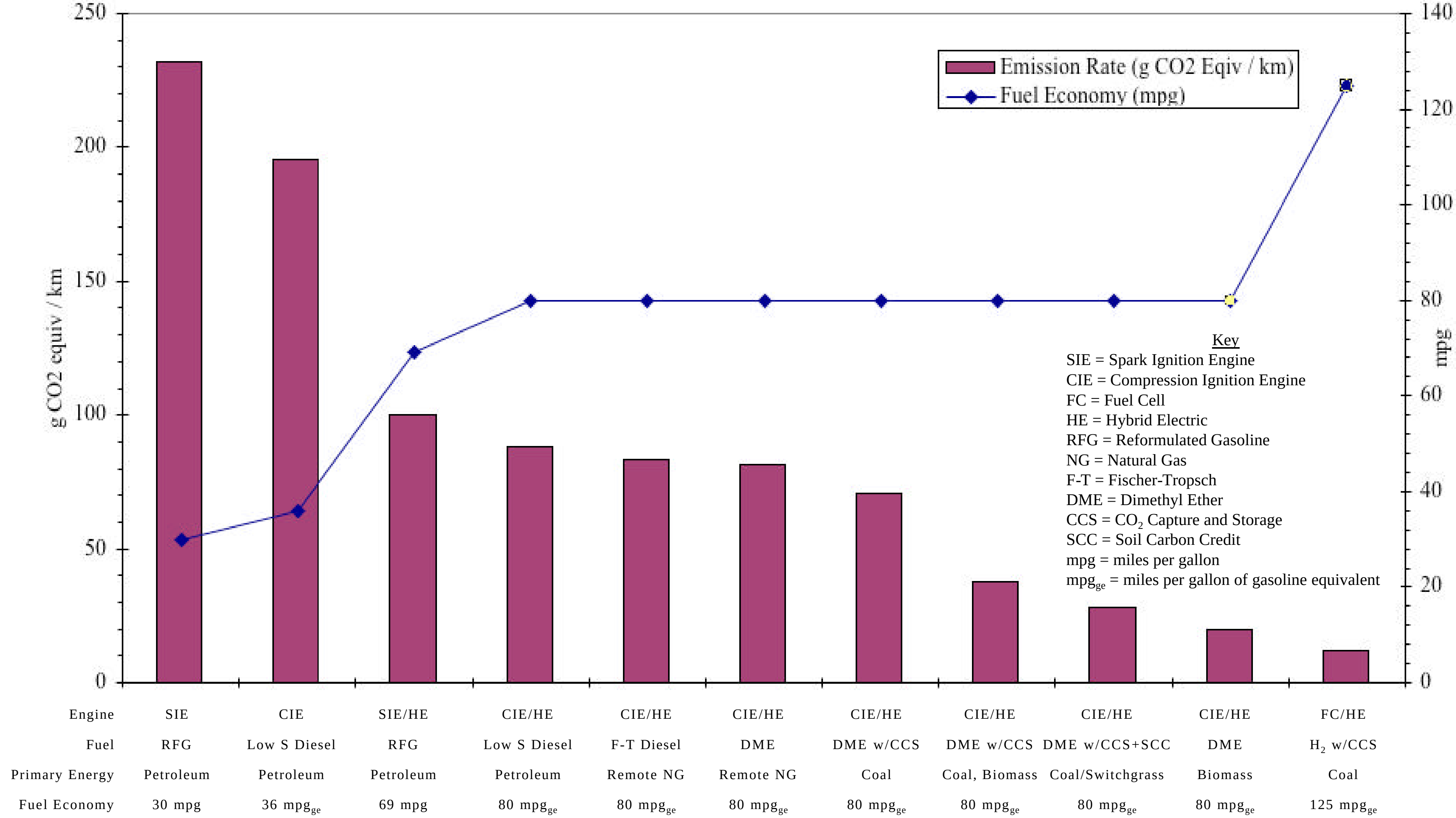
	Current technology	Advanced technology *(~ 2020)*		
	SIE	SIE/HE	CIE/HE	H_2 FC/HE
Power/weight (*kW/t*)	75	75	75	75
mpg_{ge}	30	69	80	125
Weight (t) (*w/136 kg payload*)	1.46	1.16	1.19	1.27
Drag coefficient	0.33	0.22	0.22	0.22
Frontal area (m^2)	2.0	1.8	1.8	1.8
Rolling resistance	0.009	0.006	0.006	0.006
Auxiliary power (*kW*)	0.7	1.0	1.0	1.0

Source: M.A. Weiss, J.B. Heywood, A. Schafer, and V.K. Natarajan, *Comparative Assessment of Fuel Cell Cars*, MIT LFEE 2003-001 RP, February 2003

"Designer" fuels like DME can facilitate shift to super-efficient cars

Fuel Cycle Emissions for Global Warming

(Alternative Engine/Fuel Combinations For Cars)



CONCLUSIONS

- If geological storage of CO_2 proves to be viable in gigascale applications, coal has bright future—but:
  - Stiff competition from renewables in electricity markets (*e.g., wind/CAES*)
  - Most promising markets might be those where fuels are used directly:
    - H_2 from coal with CCS very attractive…but H_2 economy is decades away
    - C-based synfuels from coal with CCS can be made climate friendly with emphasis on designer fuels that facilitate shift to energy-efficient end-use technologies
- Biomass/coal coprocessing to produce C-based synfuels is attractive option for both biomass and coal industries:
  - For coal: partial offset of CO_2 emissions from synfuel combustion
  - For biomass:
    - Opportunity to exploit negative emissions potential from H_2 production with CCS
    - Synfuels with much less land than for dedicated biofuels
    - Relieve biomass industry of responsibilities for synfuels production/marketing downstream of gasification/syngas cleanup
- Evolution of polygeneration systems:
  - Initially, liquid fuels + electricity
  - Add increasing amounts of H_2 coproduct as H_2 economy evolves

THE WAY FORWARD

- Phase out coal combustion in favor of gasification in energy conversion
- Promote gigascale exploitation of GP wind resources (*e.g.*, *via wind/CAES*)
- Conduct many "megascale" CO_2 storage demos during next 10-15 years (*including demonstration of* H_2S/CO_2 *co-storage*)
- Promote fuel-efficient transport vehicles (*CAFE or other*) to make coal synfuels with CCS climate-compatible
- Encourage thermochemical conversion route to biofuels and coal/biomass coprocessing